Preliminary temperature Accelerated Life Test (ALT) on III-V commercial concentrator triple-junction solar cells

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***Abstract*—A quantitative temperature accelerated life test on sixty GaInP/GaInAs/Ge triple-junction commercial concentrator solar cells is being carried out. The final objective of this experiment is to evaluate the reliability, warranty period, and failure mechanism of high concentration solar cells in a moderate period of time. The acceleration of the degradation is realized by subjecting the solar cells at temperatures markedly higher than the nominal working temperature under a concentrator, while the photo-current nominal conditions are emulated by injecting current in darkness. Three experiments at three different temperatures are necessary in order to obtain the acceleration factor which relates the time at the stress level with the time at nominal working conditions. However, up to now only the test at the highest temperature has finished. Therefore, we can not provide complete reliability information but we have analyzed the life data and the failure mode of the solar cells inside the climatic chamber at the highest temperature. The failures have been all of them catastrophic. In fact, the solar cells have turned into short circuits. We have fitted the failure distribution to a two parameters Weibull function. The failures are wear-out type. We have observed that the busbar and the surrounding fingers are completely deteriorated.**

***Index Terms*—Accelerated life test, ALT, reliability, concentrator, solar cells, III-V, CPV, Photovoltaics**

I. Introduction

High concentration photovoltaic (HCPV) systems seem to be one of the most promising ways to generate electricity at competitive prices for terrestrial applications [1]. The efficiency of multi-junction solar cells has increased considerably, reaching a 41.6 % efficiency in lattice matched GaInP/GaInAs/Ge solar cells and a 43.5 % in GaInP/GaAs/GaInNAs solar cells [2]. Nevertheless, the CPV community is aware of the fact that together with the efficiency increase, high reliability is essential in reducing the cost of solar electricity by extending system lifetime [3]. Aware of this problem, the CPV community has developed the standard (IEC-62108:2007) for qualifying CPV modules and assemblies [4]. Qualification tests, also called qualitative accelerated test, are designed to specify the minimum requirements that the item under test should satisfy. However, the qualification tests are not a good indicator of the item lifetime because their duration is not long enough to cause wear-out degradation. Therefore, in order to estimate the power degradation/year, the projected returns and warranty costs of high concentration solar cells, it is crucial to carry out reliability tests. Reliability tests, also known as life tests, are designed to evaluate failures, to quantify them and to understand the failure mechanism [5] to try to avoid them. Therefore, reliability tests go beyond qualification. However, up to now there is not enough accumulated experience to evaluate the reliability of concentrator III-V multi-junction solar cells because they have not been long enough in the field. Silicon modules are reliable systems which have performed very well in the field with less than 1 % degradation/yr for more than 20 years [5]. If concentrator multi-junction solar cells are expected to have a useful life similar to silicon solar cells, few concentrator solar cells would fail or degrade importantly in a real time test of practical length at nominal operation conditions. Therefore, quantitative accelerated life tests (ALT) are required to provide reliability information in a moderate period of time (weeks or months). In this study we describe the phylosophy, design, set-up, progress and the preliminary results of the temperature accelerated life test which is being carried out on sixty commercial triple-junction solar cells GaInP/GaInAs/Ge lattice matched. To the best of our knowledge, it is the first time that this kind of experiment is carried out.

II. Fundamentals of quantitative accelerated life tests

The purpose of quantitative accelerated life testing is to find out how, when, and why failures occur in the product more quickly than with data obtained under normal operating conditions. For this purpose, one of the parameters of the device under test is subjected to representative levels of stress remaining the rest of the parameters constant working under nominal operation conditions. The high levels of stress used intentionally force failures by accelerating the effects of natural aging. Assuming a physically reasonable statistical model which relates the lifetime to the level of stress through an acceleration factor, the life data from the ALT can be used to estimate the reliability functions and parameters under nominal stress levels.

It is important to point out some assumptions of ALT models:

- The failure-causing process at high stress is the same as at the nominal stress.
- A physical/chemical process causes a change in the device under test and this change progresses over time to eventually cause failure.

- The applied stress accelerates reaction rates and this acceleration can be described by a model that is adequate over the range of testing.

In this study the factor which is going to be significantly higher in order to accelerate the aging of the solar cells is the temperature. In our test the ALT model that we are going to use is the well-known and commonly used Arrhenius life-stress model which is defined with the expression 1. It has been widely used when the acceleration variable is thermal.

$$L(T) = Ce^{\frac{E_A}{kT}} \tag{1}$$

where L(T) is a temporal measurable characteristic of the device under test life which depends on the temperature, k is the Boltzmann constant and E_A is the activation energy of the mechanism which causes the failure. C is a parameter of the Arrhenius model which depends on the L(T) used.

The activation energy (E_A) of the failure mechanism which determines the acceleration factor (A_F) of the test between two temperatures, is obtained from the linearized expression of the Arrhenius life-stress model (expression 2). The activation energy is obtained from the slope of the curve Ln(L(T)) versus 1/kT. Obviously, at least three different values of L(T) obtained from three experiments at three different temperatures are necessary in order to fit the curve Ln(L(T)) versus 1/kT properly.

$$Ln(L(T)) = E_A \cdot (1/kT) + Ln(C) \tag{2}$$

Once the activation energy is calculated, obtaining the acceleration factor between two temperatures (T_1 and T_2) is direct:

$$A_F = \frac{L(T_1)}{L(T_2)} = exp\left[\frac{E_A}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \tag{3}$$

Therefore, once the parameters of the life distribution and life-stress relationship have been estimated, the same information that is available from real time tests can be obtained with the ALT.

III. Experimental approach

The methodology followed in the temperature accelerated life test which is being carried out on commercial GaInP/GaInAs/Ge triple-junction solar cells (lattice matched) presented in this work, is an adaptation from the procedure already carried out satisfactorily on GaAs concentrator solar cells [6]. As we pointed out above, the parameter used to accelerate the aging of the solar cells is the temperature and at least three temperatures are necessary to calculate the acceleration factor. Therefore, we have placed three groups of twenty solar cells inside three climatic chambers at three different temperatures. The working conditions are emulated by injecting in darkness the equivalent current that the solar cell would photo-generate in illumination at the nominal concentration level. The dark I-V curve of the solar cells is periodically monitored during the test inside the climatic chambers in order to register the time interval in which each solar cell fails. When all the solar cells have failed, the life at the test temperature can be evaluated. Once the life at the three temperatures is evaluated, the activation energy can be calculated. From the activation energy, the acceleration factor between two temperatures is obtained by means of equation 3. Finally, a reliability study is carried out to obtain the main reliability functions and parameters, and a failure analysis is accomplished in order to determine the most fragile part of the device which causes the failure. We classify the steps followed in the accelerated life tests into three parts: 1) design of the test, 2) progress of the test, and 3) data analysis. Below, the processes carried out in every part are described.

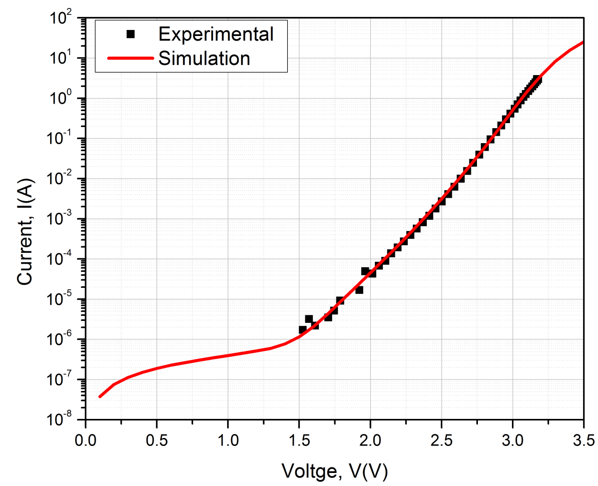

Fig. 1. Experimental measurements and simulation results of the dark I-V curve of a triple-junction solar cells used in the ALT.

A. Design of the test

In order to start the experiment the following points have to be carried out: 1) nominal working conditions under concentration have to be defined. These particular solar cells are expected to work at 820 X and 80 ^{o}C for an ambient temperature of 25 ^{o}C. 2) The current which has to be injected in darkness to emulate working conditions has to be calculated. With this purpose, simulations with our 3D distributed model described in [7] have been carried out. In order to have reliable simulations, the parameters which feed the model were obtained by fitting the experimental dark I-V curve and the illuminated I-V curve under different concentrations and spectral conditions. The excellent results of the fitting are shown in figures 1 and 2.

Once we have a reliable model, the triple-junction solar cell has been simulated under a uniform irradiance of 820 X. In figure 3 false color maps of the photo-generated current density through the top cell, middle cell and bottom cell when the solar cell operates at 820 X at the maximum power point are depicted. The current density in the active area is around

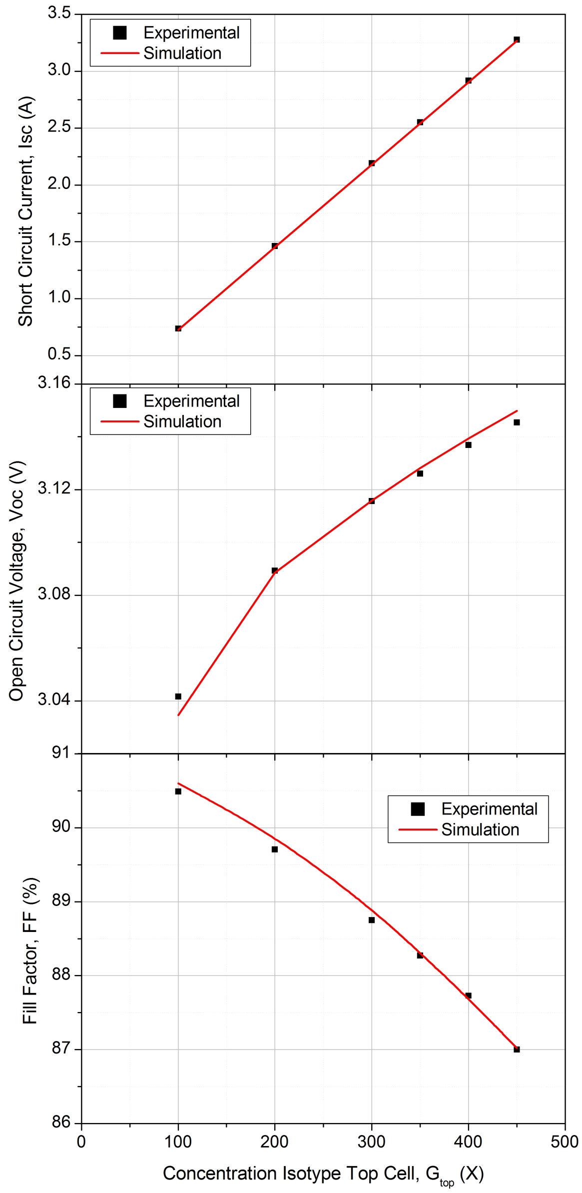

Fig. 2. Experimental and simulation fitting of the main parameters of the illuminated I-V curve of the same triple-junction solar cell presented in figure 1 under different concentrations and spectrums.

11.5 A/cm^2 and zero or negative in the bus bar and fingers. Ideally this current density distribution should be emulated in the ALT by forward biasing the solar cell in darkness but in darkness the main of the current flows beneath the busbar and fingers. We have used our 3D distributed model to simulate the distribution of the current density through the subcells when different levels of current were injected into the solar cell. We have been increasing the current injected into the solar cell so that the current density distribution in darkness was as close as possible to the current density distribution at 820 X, but without exceeding in darkness the current density photo-generated at 820 X (11.5 A/cm^2) in any point on the solar cell. Therefore, the criterion followed

TABLE I
EQUIVALENT CONCENTRATION NEEDED TO PHOTO-GENERATE THE SAME CURRENT DENSITY THAN THE CURRENT DENSITY WHICH FLOWS IN DARKNESS DUE TO THE INJECTION OF 3.2 A.

Subcell	Busbar	Fingers	Active Area
TC	450 X	470-820 X	250-340 X
MC	440 X	320 X	330 X
BC	430 X	315 X	320 X

for emulating 820 X is conservative. The maximum level of current injection which fulfilled this criterion was 3.20 A. In figure 3 the current density distribution in darkness through the different subcells when the solar cell is biased with 3.20 A is shown. The external fingers in the top cell are draining the highest current density (about 11.5 A/cm2). It should be pointed out that we have also observed this effect in experimental electroluminescence maps. Therefore, 3.2 A have been injected to the solar cells for emulating the photo-generated current at 820 X. In table I we present the equivalent concentrations which would be needed to photo-generate the current density that each subcell manage in the different regions of the solar cell when 3.2 A are injected into the solar cells in darkness.

The next step in the design of the experiment is 3) to determine the temperatures at which the tests will be carried out. It was checked that the packaging was able to handle up to 170 °C. Therefore, the temperature accelerated life tests have been carried out at the following solar cell temperatures: 113 $\pm$ 2^{o}C, 132 $\pm$ 2^{o}C and 164 $\pm$ 1^{o}C. These temperatures are high enough to obtain a significant acceleration factor and they are sufficiently separated from each other in order to evaluate accurately the activation energy value. Finally, the last step has been 4) to characterize the 60 solar cells in order to carry out a failure analysis when the tests finish. The following characterization techniques have been used: external quantum efficiency (EQE), X-ray transmission imaging of the back solder paste, I-V curve in darkness at 1X and at 400 X and electroluminescence mappings.

B. Progress of the test

The solar cells have been divided into three groups of 20 solar cells. They have been introduced into three climatic chambers at three different temperatures. In order to emulate working conditions, 3.2 A $\pm$ 0.01 A are injected to the solar cells heating them up to: 113 ^{o}C $\pm$ 2 ^{o}C, 132 ^{o}C $\pm$ 2 ^{o}C and 164 ^{o}C $\pm$ 1 ^{o}C except for two solar cell in each climatic chamber which are considered reference solar cells. After the period of current injection, all the solar cells are automatically disconnected from the current sources and there is a period of temperature stabilization. After the stabilization period, the dark I-V curve of each solar cell is measured. Once all the solar cells have been measured, the current sources are connected again to the solar cells and the cycle starts again. This cycle is repeated until all the solar cells inside the climatic chamber (except for the reference solar cells) fail. Figure 4

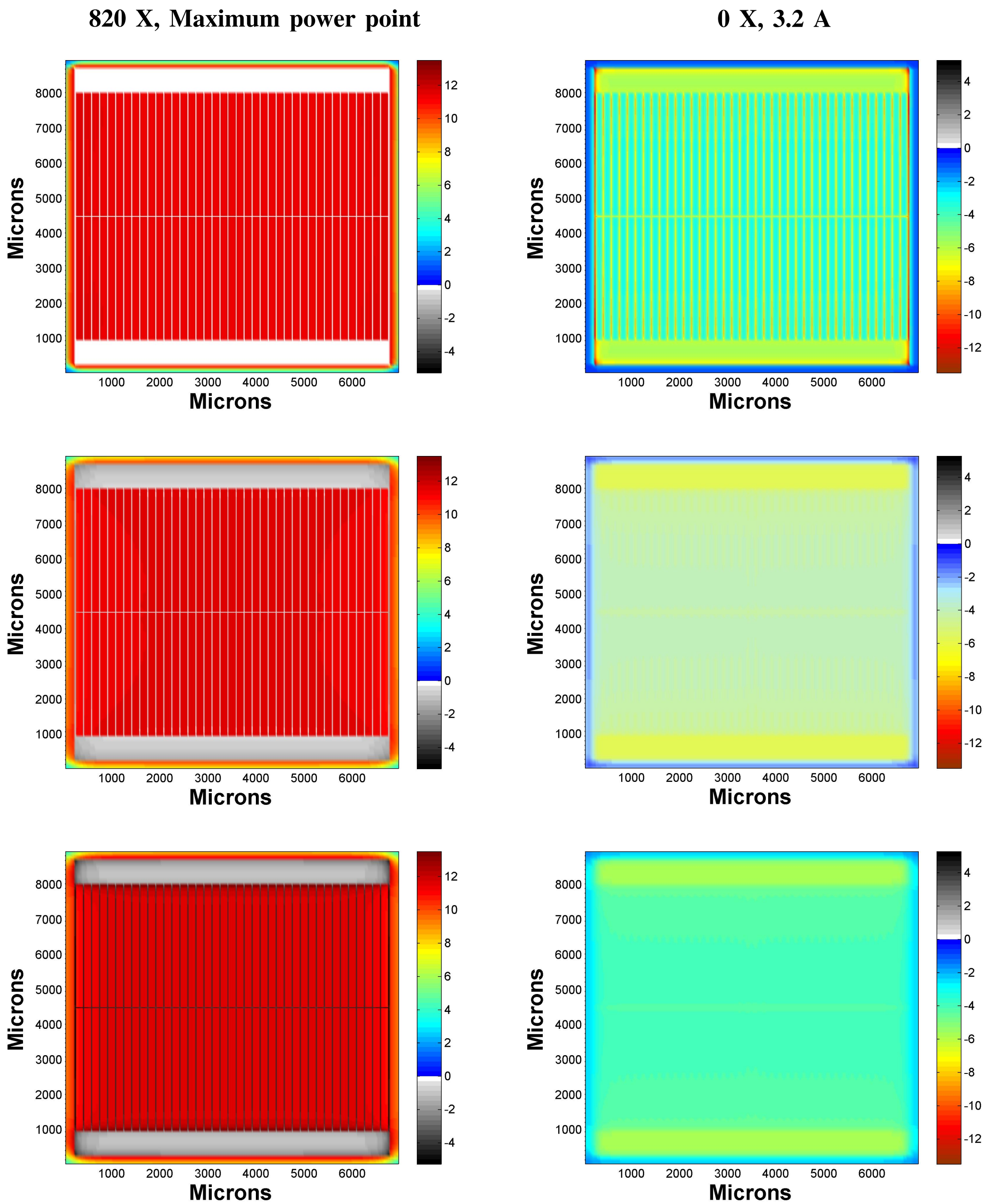

Fig. 3. False color maps representing the current density (A/cm^2) through the top cell (top figures), middle cell (medium figures) and bottom cell (bottom figures) for an illumination of 820 X at the maximum power point (left figures) and injecting 3.2 A in darkness (right figures). The vertical scale is A/cm2.

sketches the cycles of the solar cells (except the reference solar cells) inside the climatic chambers.

C. Data analysis

Once all the solar cells have failed, the analysis of accelerated life test data consists of: 1) finding a life distribution model which describes the solar cells failures at different temperatures, 2) finding a life-stress model that quantifies the manner in which the life distribution changes across different temperatures, 3) to combine the life distributions and the life-stress model to obtain reliability information at nominal working condition and finally, 4) to carry out a failure analysis to determine the part of the solar cell responsible of the failure.

Up to date, only all the solar cells of the test at the highest temperature (164 ^{o}C) have failed. Therefore, we can not calculate the acceleration factor (A_F) which relates the time at certain stress level with the time at nominal working condition (see expression 3). Consequently, complete reliability information at nominal conditions can not be obtained. Nevertheless, useful information can be derived

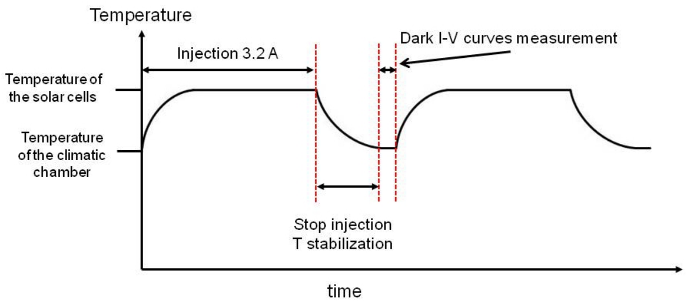

Fig. 4. Sketch of the thermal cycles of the solar cells inside the climatic chamber.

from the existing data of the solar cells tested at 164 ^{o}C.

On finding a life distribution model which describes the solar cell at 164 ^{o}C, we have decided to use the Weibull distribution, one of the most popular and widely used distribution in failure data analysis. There are different estimation methods to find the parameters of the Weibull distribution that are best suited to a given set of data. Each method has a criterion which yields estimates that are best in some situations. We have chosen the MLE (Maximum Likelihood Estimation) method which, from all possible values, it finds the parameter values which maximize the likelihood of obtaining the data. Finally, in order to account for the statistical uncertainty in estimates, 90 % confidence intervals have been used. In figure 5 the Weibull plot is shown. A reasonably good fit of the failure probability ditribution to the Weibull function is observed. The parameters of the Weibull function which reproduce the failure distribution obtained with the MLE method are:

- The minimum life parameter (γ) has been fixed to zero.
- The shape parameter β = 1.83.
- The scale parameter or characteristic life η = 32.04 hours.

In figure 6 the shape of the failure probability density function (see expression 4) can be observed. It is slightly positively skewed (has a right tail).

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{4}$$

In figure 7 the failure rate function (see expression 5) versus time is shown. The failure rate function monotonically increases corresponding with the wear-out failure part of the bathtube curve.

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{5}$$

Regarding the failure analysis, the eighteen solar cells tested have presented catastrophic failures. In fact, they have turned into short circuits. However, neither of the two reference solar cells have failed. It has to be pointed out that the reference solar cells have not been subjected to current injection and consequently they have not suffered thermal cycles either. They have been at the constant temperature of the climatic

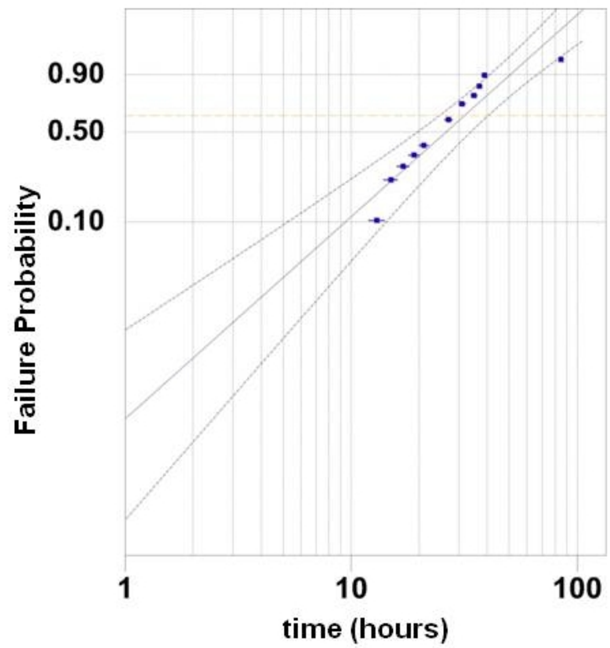

Fig. 5. Weibull plot of the failure probability versus time (hours) for the solar cells at 164 ^{o}C.

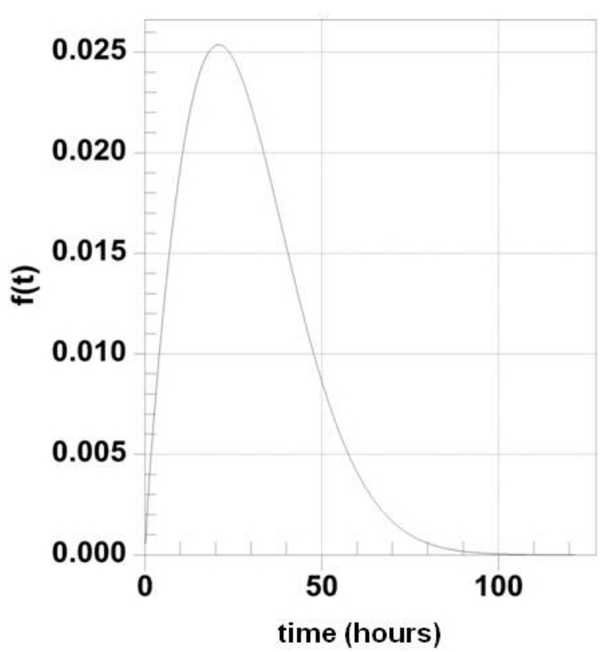

Fig. 6. Probability density function (pdf) versus time (hours) for the solar cells at 164 ^{o}C.

chamber (143 $\pm$ 1 ^{o}C) through out the whole test. Therefore, the high temperature of the climatic chamber (143 $\pm$ 1 ^{o}C) does not seem to be responsible for the failure. Due to the solar cells turned into a short circuit, we have not been able to carry out the same characterization techniques as prior to the test. We only could make a visual inspection. We have observed that the eighteen solar cells after the test present the busbar

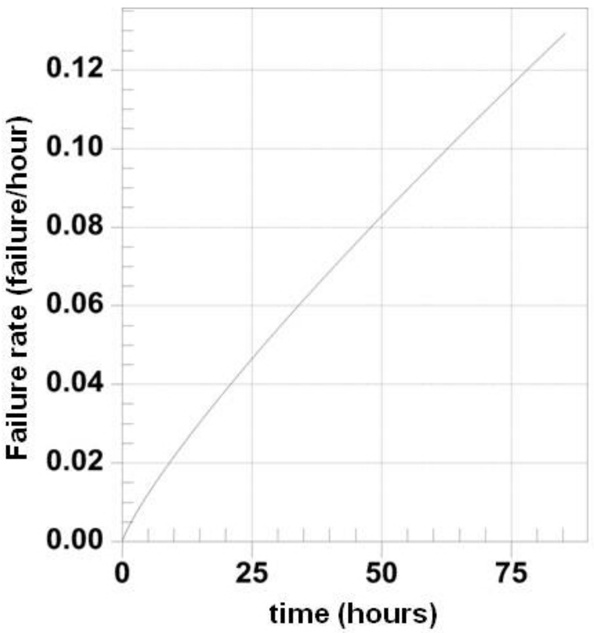

Fig. 7. Failure rate function (failures/hour) versus time (hours) for the solar cells at 164 ^{o}C.

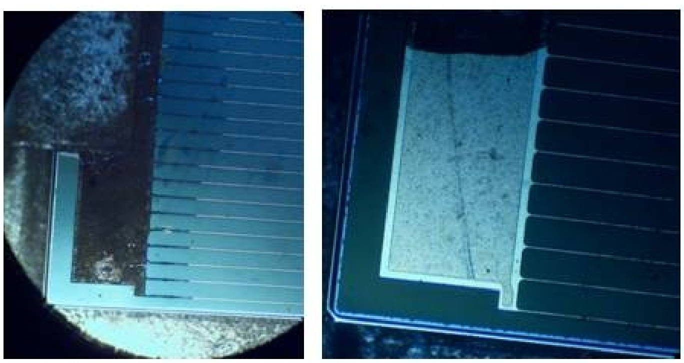

Fig. 8. Photograph of the metal deteriorated of the solar cells which were injected 3.2 A in the ALT at 164 ^{o}C (left figure) and photograph of the metal intact of the reference solar cells (right figure).

and the surrounded fingers completely deteriorated (burned out) as shown in the left photograph of figure 8. However, the reference solar cells present the metalization intact (see the right photograph of figure 8).

IV. Summary and conclusion

In this paper a quantitative temperature accelerated life test on sixty commercial triple-junction concentrator solar cells has been launched and the steps followed have been explained in detail. In order to estimate the reliability and warranty period of this solar cells under nominal working conditions, the solar cells have been divided into three groups and they have been placed into three climatic chamber at three different temperatures. The aging of the solar cell have been accelerated by stressing the solar cells at higher temperatures than nominal ones: 113 ^{o}C, 132 ^{o}C and 164^{o}C. The nominal photo-generated current under a concentration of 820 X has been emulated by injecting current in darkness. Only all the solar cells inside the climatic chamber at the highest temperature (164^{o}C) have failed. All the failures have been catastrophic, turning the solar cells into short circuits. By visual inspection we have observed that the busbar and the surrounding fingers of the solar cells tested are burned out. However, two reference solar cells which were inside the same climatic chamber at 143^{o}C have not failed and present the busbar and fingers intact. In these reference solar cells current has not been injected through them, thus they have not been subjected to thermal cycles either. The failure probability distribution of the solar cells at 164^{o}C has been fitted to the two parameters Weibull function and a good fit has been obtained with the shape parameter β = 1.83 and the scale parameter or characteristic life η = 32.04 hours. The failure probability density function is slightly positively skewed (has a right tail) and the failure rate function monotonically increases revealing that the failures are wear-out type.

Acknowledgments

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